Beneath the Electroweak Veil

Chris Quigg

Bill Bardeen Symposium · September 23, 2005

40_{16}

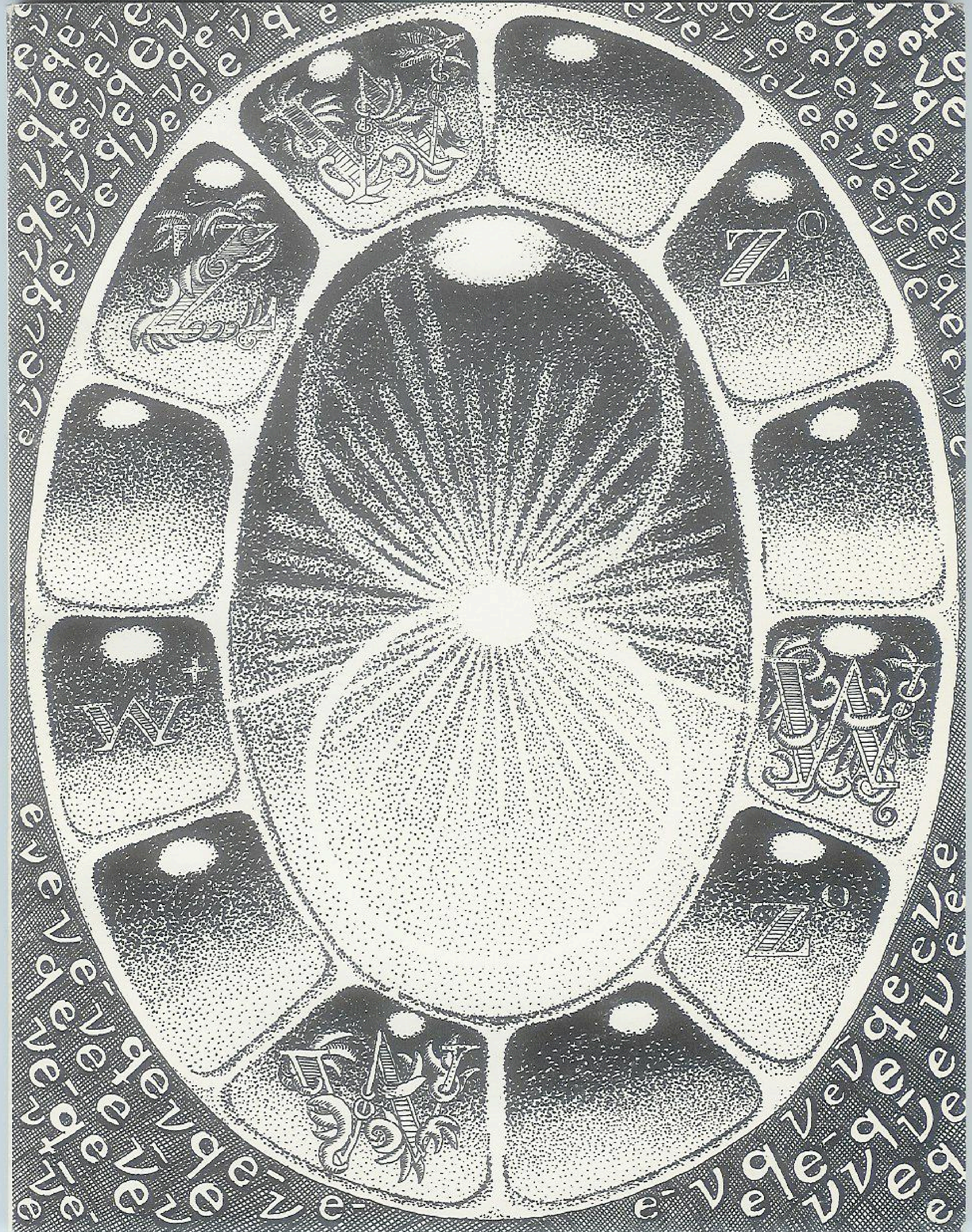
The importance of colleagues ...

June 9, 1968

To Bill

With pride in the excellent progress you have made in physics. This will show you how much easier physics was in my day.

Dad.



Ben Lee on Weak Interactions at High Energies

It's like chickenpox ... every theorist has to get it once, and it's better to get it out of the way when you are young

Step 1: Learn about the disease ...

Pomeranchuk
Appelquist & Bjorken
Novikov
Dolgov, Okun', Zakharov
Ninomiya, Nitto, Watanabe
Joglekar
Llewellyn Smith
Gell-Mann, Goldberger, Kroll, Low

Step 2: Ignore conventional wisdom

Don't start a calculation until you know the answer

Calculate everything in sight (and then some)

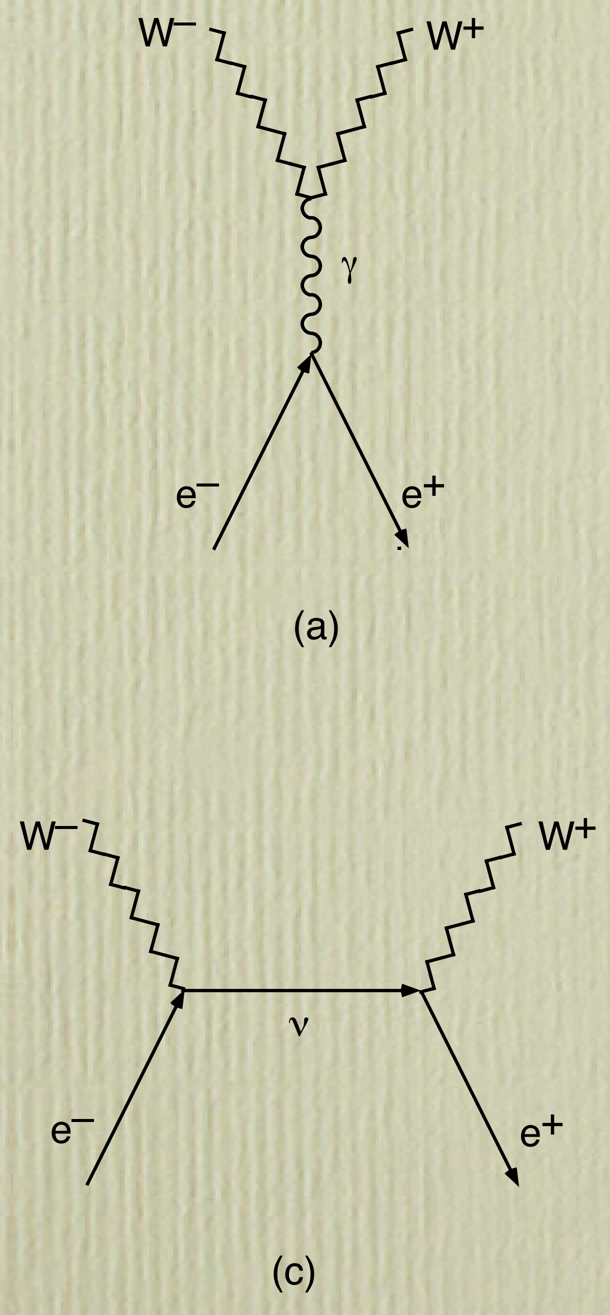
$$\nu_\mu e \longrightarrow \mu \nu_e$$

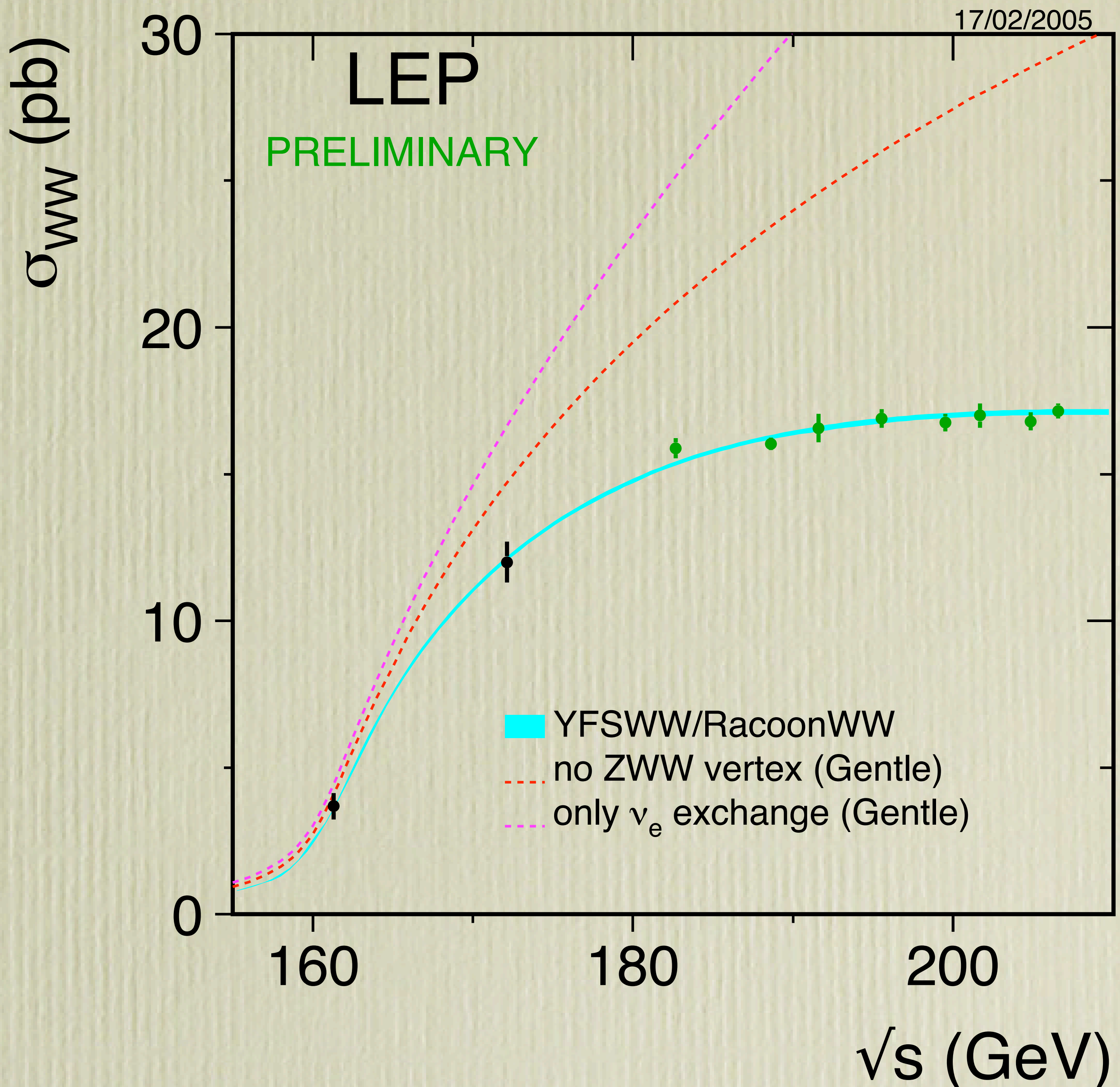
$$N/D$$

$$\bar{\nu}_e e \longrightarrow \mu \bar{\nu}_\mu$$

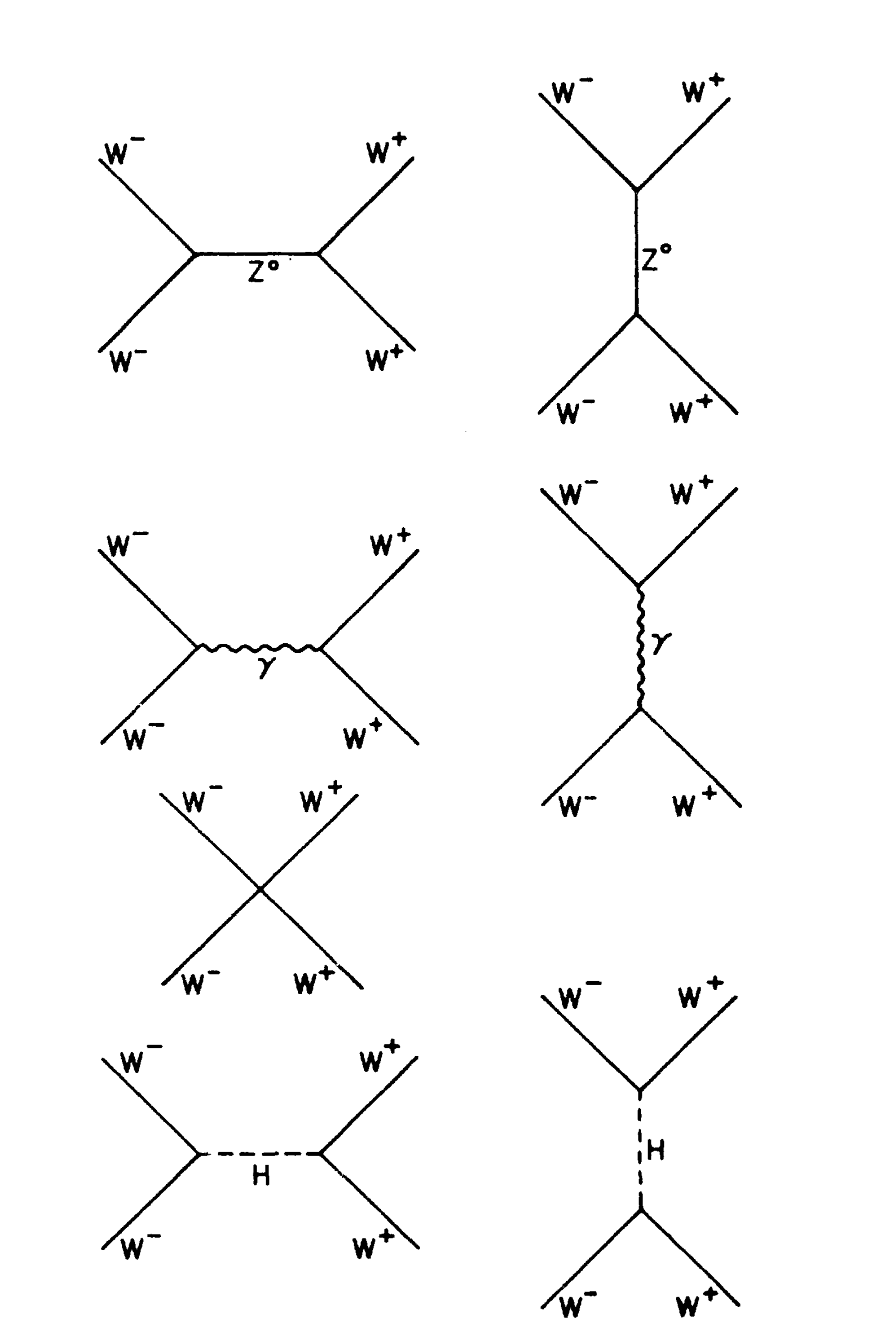
$$\nu \bar{\nu} \rightarrow W^+ W^-$$

$e^+ e^- \rightarrow W^+ W^-$ helicity amplitudes


W⁻
W⁺
γ
Z
ν
H
e⁻
e⁺
(a)
(b)
(c)
(d)


17/02/2005
LEP
PRELIMINARY
σ_{WW} (pb)
30
20
10
0
160
180
200
√s (GeV)
YFSWW/RacoonWW
no ZWW vertex (Gentle)
only ν_e exchange (Gentle)

Step 3: Throw away the leptons ...



$$T(W_L^+ W_L^- \to W_L^+ W_L^-) =$$
$$-\sqrt{2} G_F M_H^2 \left(\frac{s}{s - M_H^2} + \frac{t}{t - M_H^2} \right)$$

39 channels

Step 4: Arrange for Bill to enter the room carrying Tini Veltman's *Second Threshold in Weak Interactions?*

$$\lim_{s \gg M_H^2} (a_0) \rightarrow \frac{-G_F M_H^2}{4\pi\sqrt{2}} \cdot \begin{bmatrix} 1 & 1/\sqrt{8} & 1/\sqrt{8} & 0 \\ 1/\sqrt{8} & 3/4 & 1/4 & 0 \\ 1/\sqrt{8} & 1/4 & 3/4 & 0 \\ 0 & 0 & 0 & 1/2 \end{bmatrix}$$

Fermilab-Pub-77/22-THY

The Strength of Weak Interactions at Very High Energies and the Higgs Boson Mass

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ABSTRACT

We show that if the Higgs boson mass exceeds $M_c = (8\pi\sqrt{2}/3G_F)^{1/2}$, partial-wave unitarity is not respected by the tree diagrams for two-body reactions of gauge bosons, and the weak interactions must become strong.

* Supported in part by the Alfred P. Sloan Foundation; also at Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637.

† Operated by ...

Modern development in weak interaction theory is based upon the concept of spontaneously broken gauge symmetry.[1] Gauge theories of the weak and electromagnetic interactions contain one or more physical scalar (Higgs) particles, the existence of which is a necessity if the high-energy behavior of the S-matrix is to be reasonable.[2] In this Letter we point out that if the Higgs boson mass exceeds about 1 TeV/c² new phenomena must appear in weak interactions in the TeV energy regime. alternatively, if the Higgs boson mass is much less than 1 TeV/c², weak interactions may remain weak at all energies.[3]

We derive a quantitative estimate of this critical value of the Higgs boson mass. Our considerations are S-matrix theoretic in nature[4] and depend very little on the formal apparatus of renormalizable field theory. They rely instead on the application of unitarity bounds to tree diagrams. For definiteness we shall consider the minimal scheme of Weinberg and Salam[5] based on the group SU(2)⊗U(1), in which there is only one physical Higgs particle. Our results may readily be extended to the case of several

BWL/CQ/HBT

Heavy Higgs

CERN Seminar 4 March 77

Have been contemplating weak int. at very high energies, eg "after the W."

Popular topic for speculation before gauge theories. Now - can w.i. become strong?

We show if $M_H > (8\pi\sqrt{2}/3G_F)^{1/2}$, p.w.u. is not respected by tree diagrams for gauge boson scattering, so w.i. must become strong.

$\sim G_F^{1/2} M_H$

General conclusion not new
eg Weinberg $\sim G_F^{-1/2}$
Veltman's 2-loop radiative corrections in F.T.
our arguments are S-matrix in style.

Joglekar, CHLS, Cornwall Levin, TiKT.

S-matrix construction of W/S

$e^+e^- \to W^+W^-$

We compute in W/S model, but easy to generalize to many neutral physical Higgses.

Consider elastic scattering of gauge bosons $W^\pm, Z, H$

$W_L^+W_L^- \to W_L^+W_L^-$ $\quad T^{\gamma,Z} \sim \frac{G_F}{\sqrt{2}} s(1+\cos\theta)$

$$T \sim -\frac{4G_F M_H^2}{\sqrt{2}}$$

$$T = 16\pi \sum_J (2J+1)\, t^J P_J(\cos\theta)$$

$|t^J| \leq 1$ to t^0 $\qquad M_H^2 \leq \frac{4\pi\sqrt{2}}{G_F}$ from WW scatt.

$$\frac{G_F M_H^2}{4\pi\sqrt{2}} \leq 1 \Rightarrow$$

FIG 1

Refinement of the "bound" Consider coupled-channel problem $W_L^+W_L^-$, $\frac{1}{\sqrt{2}}Z_LZ_L$, $\frac{1}{\sqrt{2}}HH$ (HZ, $\gamma\gamma$ .. don't matter)

$$t_0 = -\frac{4G_F M_H^2}{\sqrt{2}} \begin{bmatrix} 1 & 1/\sqrt{8} & 1/\sqrt{8} \\ 1/\sqrt{8} & \frac{3}{4} & \frac{1}{4} \\ 1/\sqrt{8} & \frac{1}{4} & \frac{3}{4} \end{bmatrix}$$

$(2W^+W^- + ZZ + HH)$ has largest eigenvalue, $3/2$,

apply p.w.u. to eigenchannels

$$\Rightarrow \quad M_H^2 \leq \frac{8\pi\sqrt{2}}{3G_F} \approx (1\ \mathrm{TeV}/c^2)^2$$

for p.w.u. to be respected by the tree diag.

possibilities

$H < 2M_W$: presumably EGN scenario applies

$< M_H \lesssim 600\ \mathrm{GeV}/c^2$: $H \to W^+W^-$, Z^0Z^0

e pt estimates of $\Gamma(H\to\ldots)$

FIG 2.

be produced in LEP, etc? At resonance peak

$$(e^+e^- \to H) \approx \frac{4\pi}{M_H^2}\, \Gamma(H \to e^+e^-) / \Gamma(H \to \text{all})$$

$$\frac{\Gamma(H\to e^+e^-)}{M_H} = G_F m^2 / 4\pi\sqrt{2}$$

200, $\quad \sigma \approx 10^{-33} \left(\frac{m}{1\ \mathrm{GeV}/c^2}\right)^2\ \mathrm{cm}^2$

$< 10^{-39}$ for e^+e^- (depressing)

$\left(\frac{1}{40}\right) \times$ "R"

ZH $\quad \sigma \approx$ few $\times 10^{-35}$ @ $\sqrt{s} = 300$

$H \gtrsim 600\ \mathrm{GeV}/c^2$: $\Gamma_H \gtrsim 100\ \mathrm{GeV}/c^2$

$M_H \gtrsim M_C$, SI among gauge bosons may reate a scalar bound-state of low mass hich serves as a phenomenological Higgs
No demonstration

(Less daring) $M_H \gtrsim M_C$, WI $\to$ Strong and begin to isplay attributes of SI in GeV region.

IVB resonances, multiple prod of IVB, etc.

ew phenomena, in addition to IVB, are to overed at energies not much larger than 1 TeV.

Either light Higgs or WI get strong

Similarity of our speculations to Veltman's

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NU

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN

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March 4, 1977

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Dear Ben,

The answer is

$$\sigma = \frac{G_F^2 M_Z^6}{4\pi} \frac{(1-4x+8x^2)}{(s-M_Z^2)^2}\left[1+\frac{K^2}{3M_Z^2}\right]\left(\frac{2K}{\sqrt{s}}\right),$$

where K is the cm momentum of the outgoing H, Z, and $x = \sin^2\theta_W$.

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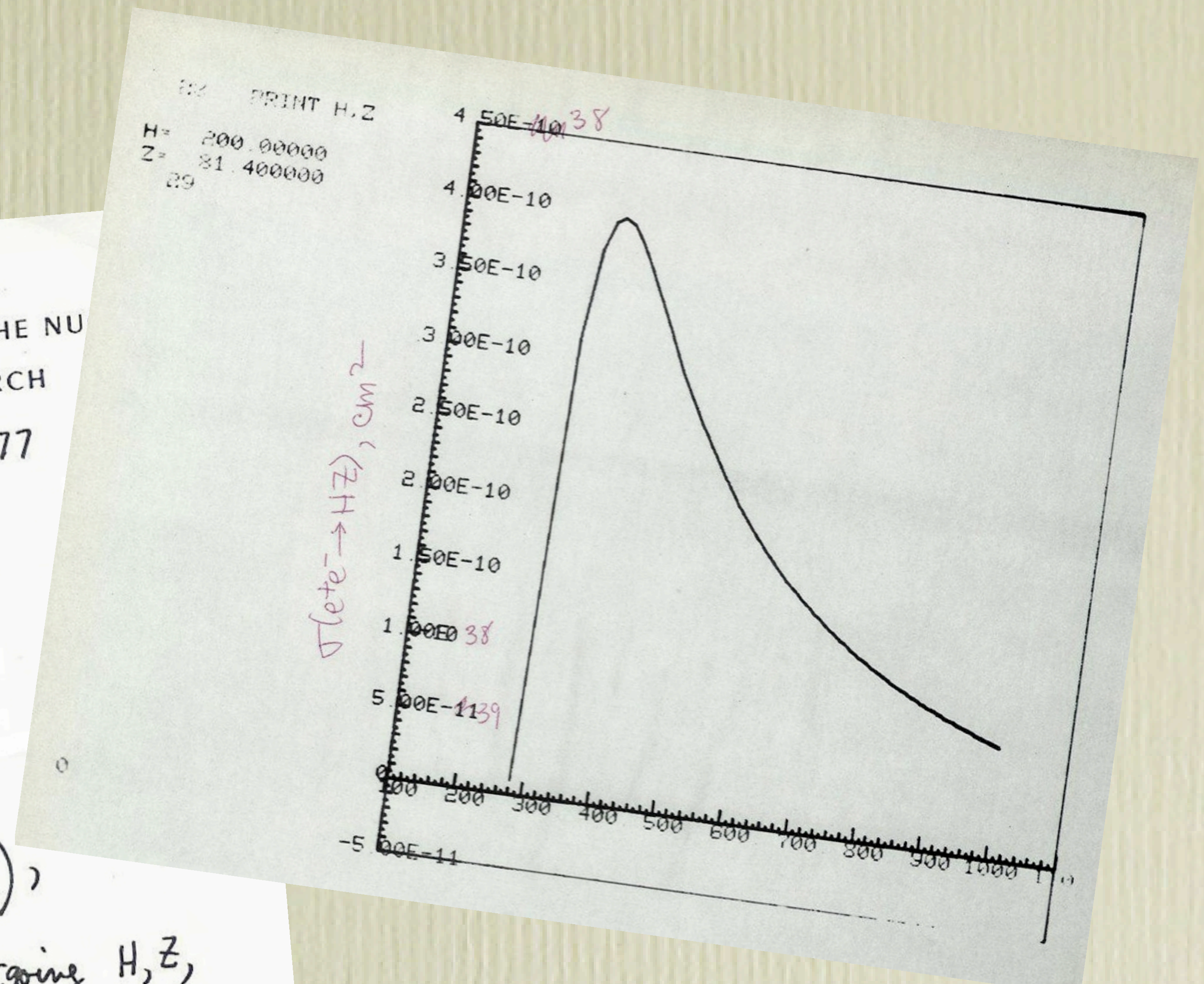


The conditional upper bound (~~3.6~~ 1.1) on the Higgs boson mass leads us to contemplate the heavy Higgs alternative, $M_H > 2M_W$. A Higgs boson in this mass range has the striking property that it decays almost exclusively into pairs of intermediate bosons. If the mass of the Higgs boson is substantially less than the critical mass, say $2M_W < M_H \lesssim 600$ GeV/c^2, we expect that perturbative estimates of the production and decay ~~widths~~ rates should be reliable. For the intermediate boson decay modes, we find

$$\frac{\Gamma(H \to W^+W^-)}{M_H} = \frac{G_F M_W^2}{8\pi\sqrt{2}} \frac{(1-x)^{\frac{1}{2}}}{x} (3x^2 - 4x + 4) \, , \qquad (5.2)$$

$$\frac{\Gamma(H \to Z^0Z^0)}{M_H} = \frac{G_F M_W^2}{16\pi\sqrt{2}} \frac{(1-x')^{\frac{1}{2}}}{x} (3x'^2 - 4x' + 4) \, , \qquad (5.3)$$

where $x = 4M_W^2/M_H^2$ and $x' = 4M_Z^2/M_H^2 = x/\cos^2\theta_W$. The resulting partial decay widths are shown in Fig. 13. It is amusing to note that because of its peculiar decay properties, a heavy Higgs boson may have a more distinctive experimental signature than a light one. The chain

$$H \to Z^0 Z^0, \quad Z^0 \to \ell^+\ell^-, \quad Z^0 \to \ell^+\ell^-$$

would be rather unmistakable.

More promising is the production of H in association with an intermediate boson. A simple example is the reaction

$$e^+e^- \longrightarrow Z_{\text{virtual}} \longrightarrow ZH, \tag{5.6}$$

which occurs with a cross section[16]

$$\sigma(e^+e^- \to HZ) = \frac{\pi\alpha^2}{24}\left(\frac{2K}{\sqrt{s}}\right)\frac{(K^2+3M_Z^2)}{(s-M_Z^2)^2}\,\frac{(1-4x+8x^2)}{x^2(1-x)^2}, \tag{5.7}$$

where $x = \sin^2\theta_W$ and K is the c.m. momentum of the emerging particles. At very high energies, for which $2K \longrightarrow \sqrt{s}$, the ratio

$$r \equiv \frac{\sigma(e^+e^- \to HZ)}{\sigma(e^+e^- \to \mu^+\mu^-)} \longrightarrow \frac{(1-4x+8x^2)}{128\,x^2(1-x)^2} \tag{5.8}$$

The Higgs Boson will be found

... whether it exists or not!

If EW symmetry were not hidden …

QCD confines quarks into color singlets
nucleon mass would be little changed …

~~$SU(2)_L$ confines into weak isospin singlets~~

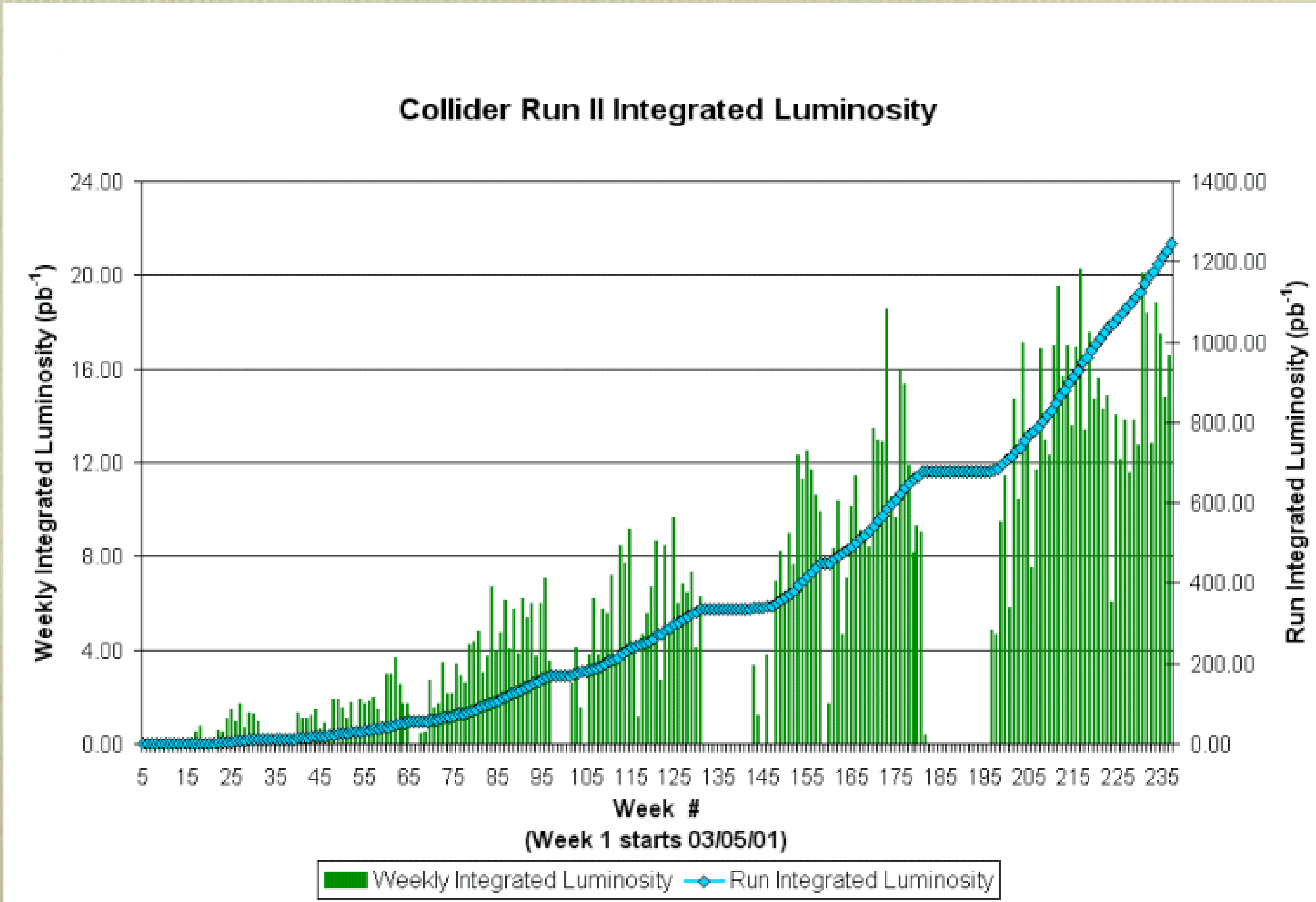
QCD breaks $SU(2)_L \otimes U(1)_Y$ to $U(1)_{em}$

proton outweighs neutron; rapid β decay
lightest nucleus: neutron — no hydrogen atom

some light elements produced in the big bang
but the radius of atoms is infinite

no atoms, no chemistry, no liquids, no solids

How is our thinking too narrow?



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Weekly Integrated Luminosity (pb-1)
Run Integrated Luminosity (pb-1)
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16.00
12.00
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1400.00
1200.00
1000.00
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600.00
400.00
200.00
0.00
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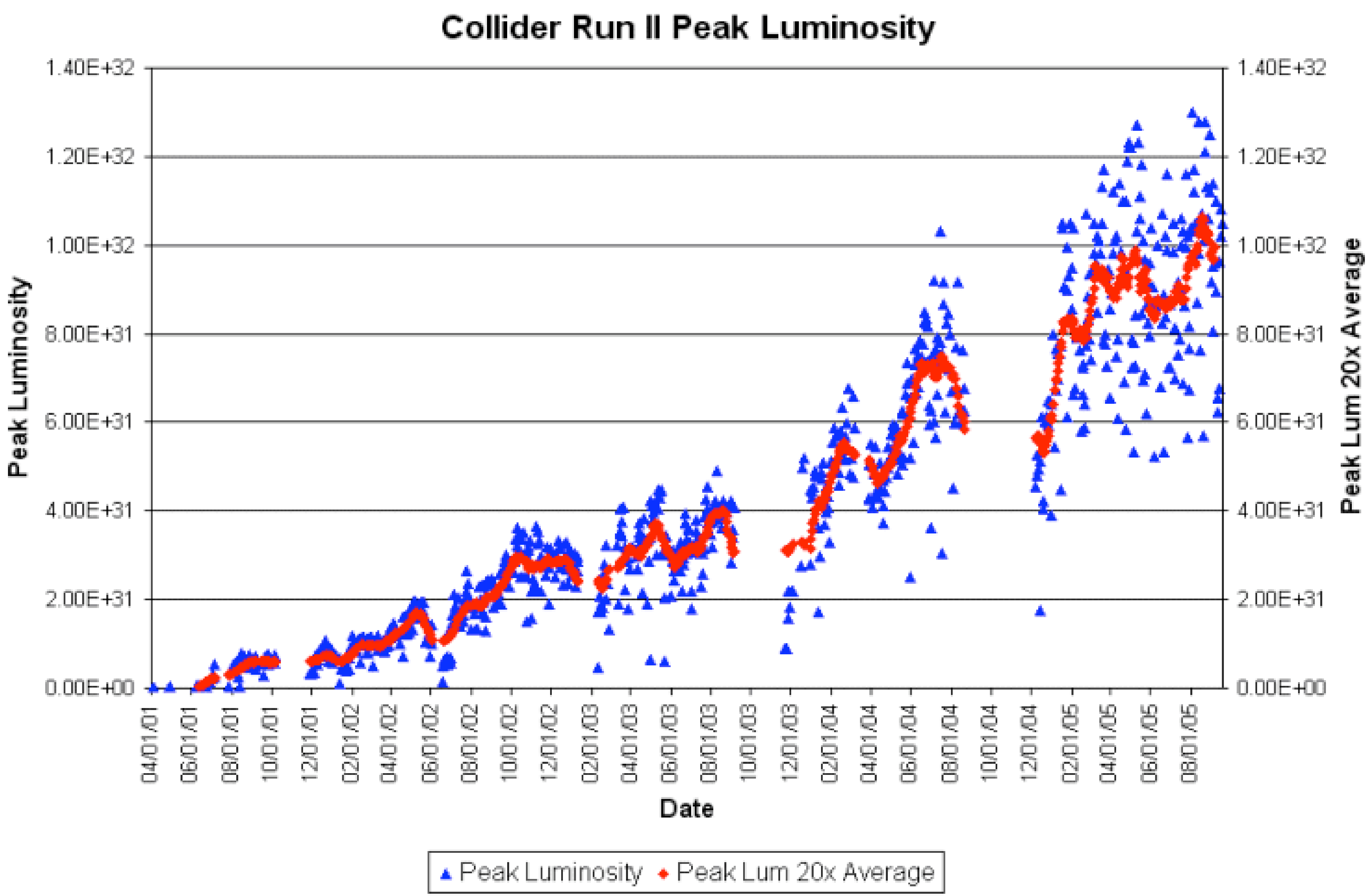
Week #
(Week 1 starts 03/05/01)
Weekly Integrated Luminosity
Run Integrated Luminosity



Collider Run II Peak Luminosity
Peak Luminosity
Peak Lum 20x Average
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2.00E+31
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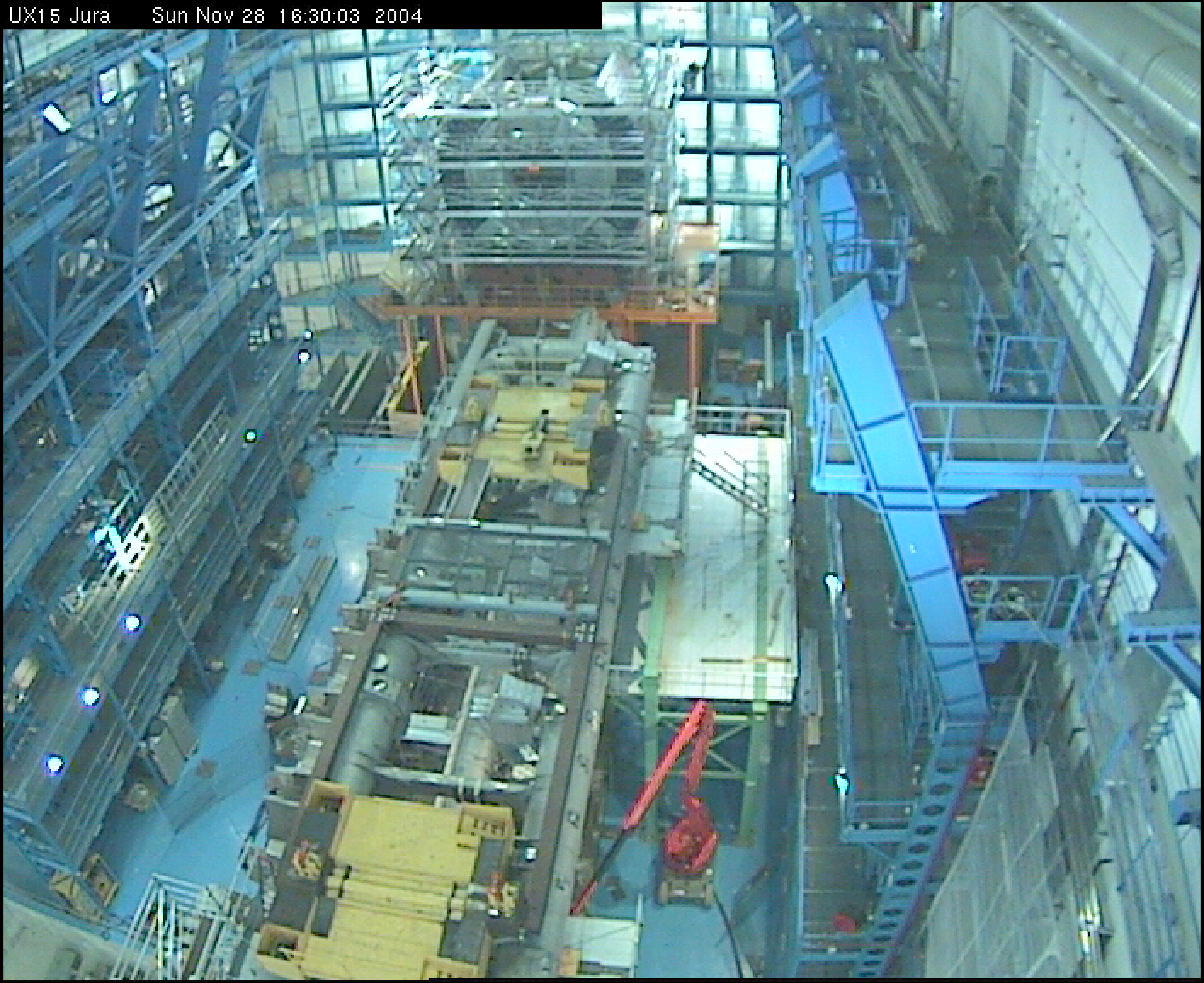
Peak Luminosity
Peak Lum 20x Average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